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Discrete Normal Mode Decompositions in Quasigeostrophic Theory

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The baroclinic modes of quasigeostrophic theory are incomplete and the incompleteness manifests as a loss of information in the projection process. The incompleteness of the baroclinic modes is related to the presence of two previously unnoticed stationary step-wave solutions of the Rossby wave problem with flat boundaries. These step-waves are the limit of surface quasigeostrophic waves as boundary buoyancy gradients vanish. A complete normal mode basis for quasigeostrophic theory is obtained by considering the traditional Rossby wave problem with prescribed buoyancy gradients at the lower and upper boundaries. The presence of these boundary buoyancy gradients activates the previously inert boundary degrees of freedom. These Rossby waves have several novel properties such as the presence of multiple equivalent barotropic modes, a finite number of modes with negative norms, and their vertical structures form a basis capable of representing any quasigeostrophic state. Using this complete basis, we are able to obtain a series expansion to the potential vorticity of Bretherton (with Dirac delta contributions). We compare the convergence and differentiability properties of these complete modes with various other modes in the literature. We also examine the quasigeostrophic vertical velocity modes and derive a complete basis for such modes as well. In the process, we introduce the concept of the quasigeostrophic phase space which we define to be the space of all possible quasigeostrophic states. A natural application of these modes is the development of a weakly non-linear wave-interaction theory of geostrophic turbulence that takes prescribed boundary buoyancy gradients into account.